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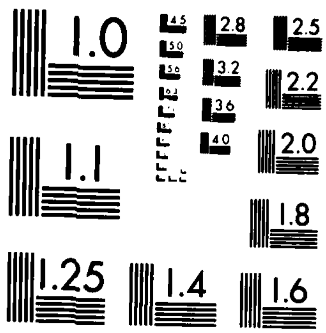

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AFOSR-TR- 85-0379

LARGE EDDY STRUCTURES IN TRANSITIONAL AND TURBULENT FLAMES

Second Annual Report

AFOSR Contract No. 82-0266

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July 1984

Abstract

A second generation experimental apparatus has been designed and constructed to provide a uniform co-flowing air stream with no physical enclosure around the flame. A new seeding system has been acquired from Wright Patterson AFB that provides large quantities of small seeded particles in the secondary air to avoid bias in velocity measurements by LDV. More flame height measurements have been made which do not agree with the classical Hawthorne-Hottel data. The LDV electronics processing data acquisition and software systems have all been debugged, calibrated and made ready for measurements with sampling times of 150 KHz. Ionization and thermocouple probes have been designed and are under construction. Preliminary color schlieren photographs using rainbow schlieren have been made. Computations in collaboration with NRL have been initiated.

Introduction

During the second year of the current contract the experimental apparatus was redesigned and a second generation system was constructed to provide a uniform velocity and turbulence intensity co-flowing air stream with no physical enclosure around the flame. Under these conditions the boundary conditions around the complete flame boundary are uniform and steady. The unconfined flow system allows easy access for several probes and traversing mechanisms. The large diameter (3 ft.) secondary air flow shields the flame, aerodynamically, from influence of convection in the laboratory and maintains the flame in a central location with axial symmetry. The combination of blowing for the secondary air and strong suction through a large diameter (3 1/2 ft.) conical exhaust duct ensures capture of all particles in the exhaust system without the necessity of providing an enclosure. The flame configuration at CMU is similar to the system for studying jet flames that is under construction at Wright Patterson AFB so that direct comparisons will be possible between different diagnostic techniques. Any difference in measured data will need to be explained.

Great care and trouble has been taken to ensure adequate, uniform, small particle seeding for the secondary air flow to avoid bias errors in LDV measurements. Dr. Nejad of Wright Patterson AFB has been most helpful in supplying CMU with a specially designed seeder which has the capability of providing the large quantities of seed required to fully and uniformly seed the large volume secondary air flow.

The flame height measurements reported in the first annual report have been continued. There are very distinct differences between our measurements and those

reported in the literature. The classical picture of flame height reported by Hottel and Hawthorne needs to be reconstructed in the light of evidence reported by ourselves and other supporting evidence published in the literature.

A great deal of time, effort, and energy has been expended on debugging, calibrating, and proving the TSI LDV system including the signal processor and data acquisition system. Much work was required to develop software for the PDP 11/34 and the MINC 23 in order to provide a LDV system capable of sampling the flow at a rate of 150 KHz.

Dr. Joao Ventura, who worked with Prof. Chigier in Sheffield for 4 years and is currently a professor at the Lisbon Institute of Technology is working with the CMU research team for one month during the summer to help in the design and construction of ionization probes and thermocouples that were developed and extensively used in Sheffield.

The initial results with color Schlieren photography, with assistance and advice from the NASA Lewis Research Center are very promising. Work will be resumed as soon as the large Schlieren mirrors which are on loan from Kirkland AFB are returned to CMU after the summer.

Kenneth Laskey (Ph.D. student) is spending 2 months over the summer working with Dr. Elaine Oran and the Naval Research Laboratories in Washington, D.C. to learn the computational codes and to address the special problems associated with computations that are directly related to the CMU flame geometry.

Experimental Apparatus

The second generation burner facility shown in Figure 1 has been completed and is now being used for measurements. Studies are presently concentrating on the 5 mm stainless steel nozzle described in previous reports.[1] Four Granger 4C448 shaded pole blowers mounted at the secondary air inlet provide the coflowing air stream. Each blower is rated at 465 CFM free air and 227 CFM across a 0.5" static pressure drop. The bottom plenum is 48" square and 14" high. Two perforated sheets, one mounted 11" above the bottom of the plenum and one mounted at the plenum exit, provide the flow resistance necessary to produce a uniform air flow. The perforated sheets are made from 20 gauge carbon steel and are perforated with 1/16" holes located on 3/16" staggered centers. The air then flows thru the center section, a round duct 3' in diameter and 14" high. The upper section, identical in size to the middle section, contains the secondary

air flow straightener at its entrance. The flow straightener is composed of approximately 21,000 drinking straws, each 1/4" in diameter and 7 3/4" long, packed in the duct. At the exit of the flow straightener is a wire cloth stretched in a hoop frame. This screen, made from 304 stainless steel 55 mesh produces a fine scale turbulence which should decay before the secondary air flow reaches the nozzle exit. The unit is sized so that a 4' high flame will still be surrounded by the uniform air flow at the flame tip.

Seeders for LDV

Two different seeding systems are currently being used for the LDV. A small fluidized bed cyclone seeder (Figure 2) using alumina in powdered form (particle size - 0.3 μm) provides the seeding for the fuel while a much larger seeder, which produces TiO_2 from $TiCl_4$, designed at Wright-Patterson AFB[2] provides the seeding for the secondary air flow surrounding the flame. A detailed description of this seeder is given in the reference. The seeding of the secondary air stream is necessary to avoid any biasing of the velocity measurements within the diffusion flame.

Providing adequate and uniform seeding for the large cross sectional area (6567 cm^2) has proved to be a difficult task. The exhaust system has been reconstructed to ensure complete removal of all dust particles for reasons of safety and to prevent deposition on lenses and other optical surfaces.

Flame Height

Flame height measurements were reported in the first annual report[1]. Additional flame height measurements have been made with changes in burner geometry. It had been found previously[1] that changing the burner exit velocity profile from a uniform to a fully developed turbulent pipe distribution had no significant effect on flame height. Because of this, the burners used for this study were three straight, stainless steel tubes having constant internal diameters of 1.52 mm, 4.39 mm, and 9.42 mm throughout their respective lengths. Again, flame heights were measured visually using two meter sticks attached to the burner assembly on either side of the flame. The secondary air velocity in all cases was maintained constant at 0.5 m/sec.

The measured visible heights of the flames were based on the average vertical distances from the burner exit to the location of the flame tip. As noted by Becker and Liang[3], the method of direct visual observation is the most appropriate measure of average flame height.

Data for hydrogen, methane, and propane flames are plotted in Figure 3 as flame height versus fuel flow rate. Some similarity can be seen between the three sets of curves. For each gas, the larger the burner exit diameter the greater the visible flame height for a given fuel flow rate. The classical Hottel and Hawthorne[4] description of flame height, in which flame height decreases with increase in fuel velocity following transition could only be found when the smallest diameter tube was used for each gas. Our data do not show the constant flame height with increasing fuel velocity in the turbulent region. A review of the literature on experimental studies of flame height revealed that results similar to ours have been reported by Baev and Yasakov[5] and Shevyakov and Komov[6].

LDV Systems and Optics

Currently, there are two Laser Doppler Velocimetry systems in use in the Mechanical Engineering laboratories at Carnegie-Mellon Unviersity. They are:

. An Argon-Ion laser based, dual velocity-component system

. A He-Ne laser based, single velocity-component system

The first system is based on an eight-watt Argon-Ion laser and has the capability of simultaneously measuring two velocity components. The second system is based on a fifteen milliwatt He-Ne laser and measures a single velocity component. Each system operates with its own minicomputer, either a PDP-11/34 or MINC-23.

The accompanying optics include:

(1) Six lenses (two each) of focal lengths 104.6, 242 and 573 mm.

(2) Two beam expanders of ratios 2.27 and 3.75.

(3) One lens of 762 mm focal length.

(4) Two beam spacers of 9 mm and 22 mm spacings.

These optics provide a range of fringe spacings between 1.1 μm and 40 μm. All optics are products of TSI Incorporated.

LDV Software

Research in LDV measurements, here at CMU, over the past year has resulted in the development of software designed specifically for high-speed acquisition and graphical display of LDV data. This software is compatible with both the PDP-11/34 and MINC-23 minicomputers being used in the laboratories.

The graphical support for these two systems includes a time-history plotting package and a histogram plotting package. Time-histories provide a plot of the acquired velocities vs. their time of acquisition. This gives the researcher a

means of visually detecting structures that may exist within the flow under study. Histograms, on the other hand, display the estimated probability of occurence of a specific range of velocities.

All LDV data acquisition is done via Direct Memory Access, a high-speed form of data transfer. Recently, we conducted an experiment to determine the maximum rate of sampling via the signal processors and minicomputer. A voltage-controlled oscillator signal was used as the input to the signal processors. This simulated a flow with a high concentration of seeding particles such that at any given instant in time a single particle would be in the measurement volume. We found the sampling rate to be approximately one sample every seven to eight microseconds (Figure 4). Therefore, provided we have a flow with a high concentration of seeding particles, our LDV system is capable of sampling the flow at a rate between 125 KHz and 142 KHz. At present, we have found this quite adequate for our research needs.

Thermocouple Design

The primary emphasis in this portion of the investigation is the measuring of flame temperature fluctuations. Since such fluctuations are of high frequency, thermocouple (time) response is at a premium. By utilizing fine diameter wires (25-50 μm) the design depicted in Figure 5 has low thermal inertia and consequently a fast time response. As shown, the wires are held in place by larger diameter support wires, sheathed in alumina tubing. Because of the small diameter of the fine wires, resistance to mechanical stresses is very poor, thus necessitating that the length of the fine wire be kept at a minimum. The alumina sheathing is used to introduce mechanical rigidity of the assembly thus allowing good spatial resolution.

Though the short span thermocouple does offer good response, it also results in flame disruption. Consequently, a second design has been proposed to minimize perturbations caused by intruding instrumentation. In this approach (Figure 6), an aluminum yoke supports a larger active length of larger diameter wire. Where the first design often permitted the ceramic sheath to enter the flame flow, the latter design allows only the active thermocouple wire to come into actual contact with the flame. Since both criteria, maximum time response and minimum flame disruption, are significant, both designs of thermocouple need to be pursued to determine the limitations of each.

Also under development is a circuit for pulse heating the thermocouple

and recording the subsequent decay curve. Ensemble averaging of these curves will allow the time constant to be calculated. This time constant then allows for accurate compensation of the thermocouple. Completion of this system will allow incorporation of temperature fluctuation data into the analysis of flame structures.

Ionization Probes

Ionization probes will be used to obtain information on the location and movement of the flame front. The ionization probe consists of a negatively biased wire, which attracts positive ions. A second electrode is necessary to close the circuit. This may be the burner itself; but, because in our studies the need will arise to make measurements in lifted-off flames, the second electrode will be a wire mesh placed across the flame in good contact with it downstream of the measuring position. Hydrocarbon flames produce positive ions which, by their concentration, indicate very clearly the flame front position. The probe has a good spatial resolution and time response, hence this technique provides a very effective diagnostic tool to study the flame front geometry and measurement.

For studies in hydrogen flames which have no natural ionization, the flames can be seeded with alkali metals and in this case, the ionization will indicate regions of high temperature, which will be interesting to compare with temperature fluctuation measurements made by the thermocouple.

The signal from one probe, once digitized and stored, can then be further processed. Typically, when probing the flame's turbulent region, the signal is a random sequence of peaks, rising above a base level. Software to process the signal is already available at CMU. Peak analysis of the signals will allow the identification of particular structures in the flow (structures which have recognizable signatures).

Power spectra will give the dominant frequencies in the signal, related to the arrival of burning structures at the probe sensor, which may be different from frequencies obtained from velocity measurements. Its inverse Fourier transform, which is the autocorrelation of the signal, will permit the calculation of integral time scales, which again will be interesting to compare with those obtained from LDV velocity data.

Once this first set of data has been obtained, we will then proceed to 1) use an array of ionization probes; 2) use the ionization probe in connection with other instrumentation.

The first development requires that signals from all probes should be sampled simultaneously. From the several time histories, it will be possible to follow the path of a burning structure.

Using the ionization probe connected to other instruments, e.g. a thermocouple, will permit either 1) recording of both signals and cross-correlating them or building joint probability density functions or 2) use the probe as a trigger to initiate the thermocouple sampling. By this means, it will be possible to ensemble average temperature signals and improve our present knowledge of these burning structures in terms of their temperature characteristics.

Rainbow Schlieren

Color schlieren photography is one of the methods employed for flow visualization within the flame. The technique known as "Rainbow Schlieren"[7] has been adapted to the existing experimental apparatus. A standard Z-type configuration has been arranged (Figure 7) with the following components:

- two 30.5 cm diameter spherical mirrors each having a focal length of 3.66 m
- 162W mercury arc lamp
- rainbow apertures
- 35 mm camera

The technique is termed "rainbow" schlieren because a rainbow-like aperture is placed at the focal point of the imaging mirror. This aperture is a 35 mm slide of concentric rings of color, the core being clear surrounded by rings of blue, green, yellow, orange, and red. Density differences in the flame are indicated by different colors in the schlieren image, produced by differing amounts of light deflection through the test section of the flame. The clear central region is the same size as that of the undeflected beam from the arc lamp at the focal point of the imaging mirror. The total diameter of the aperture is determined by the maximum deflection of the light while passing through the flame. For different flames, the maximum deflections are different while the size of the core remains the same. Because of this, a series of apertures of different diameters have been made.

Work on the schlieren system has been temporarily suspended because the mirrors, which are on loan, were returned to Kirkland AFB at their request. The schlieren studies will resume once the mirrors have been returned to CMU.

Computations

A parallel computational effort is underway in cooperation with the Naval

Research Laboratory. Work is concentrating on a two-dimensional explicit finite difference code which models the full Novier-Stokes equations. A second-order Runge-Kutta scheme in time is augmented with the FCT algorithm to give fourth-order accurate phases and minimize residual numerical diffusion. Using timestep splitting, the solution of the convection problem can be coupled with other physical processes which the analyst wishes to model. Currently, a global induction parameter model[9] which simulates chemical reaction and energy release is being incorporated into the code. This model describes the chemical induction time of a mixture and allows for release of energy over a finite period of time. The specific gases for which the model has presently been calibrated are stoichiometric mixtures of hydrogen and methane in air. Scaling factors are included to account for nonstoichiometric mixtures. The code also makes use of the outflow boundary condition[10] to reduce the impact of a finite computational domain.

The present modeling effort is directed toward implementing a geometry in the code which will closely approximate the experimental apparatus. The mixing of coflowing streams of fuel and air are being investigated under nonreacting and reacting conditions. The present goal is to understand the effect of reaction on the eddy structures formed in the nonreacting flow.

Professional Personnel Directly Associated With Research Effort

Prof. Norman Chigier, W.J. Brown Professor
Kenneth Laskey, Ph.D. student
Thomas Zsak, M.E. student
Caroline Perlee, M.E. student (electrical engineering)
Gary Novay, computer systems analyst
John Feeney, electronic technician
James Martin, technician
Dr. Joao Ventura, visiting research scientist

Interactions with the Air Force

. AFOSR Contractors' meeting, Scottsdale, Arizona, September, 1983.
. ONR meeting, Pittsburgh, PA, June, 1984.
. AFOSR Contractors' meeting, Pittsburgh, PA, June, 1984
. Wright Patterson AFB, Seminar, June, 1984

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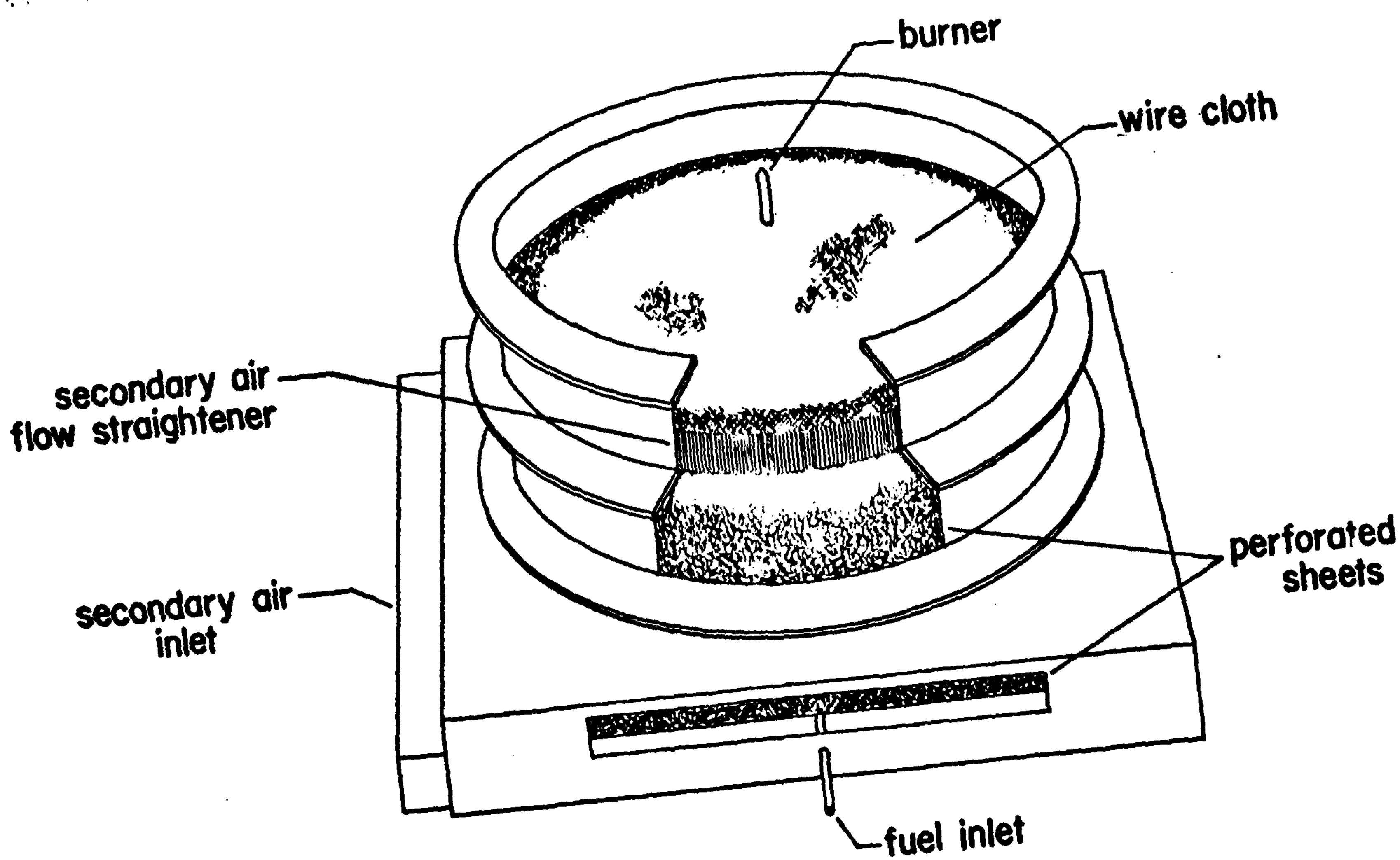
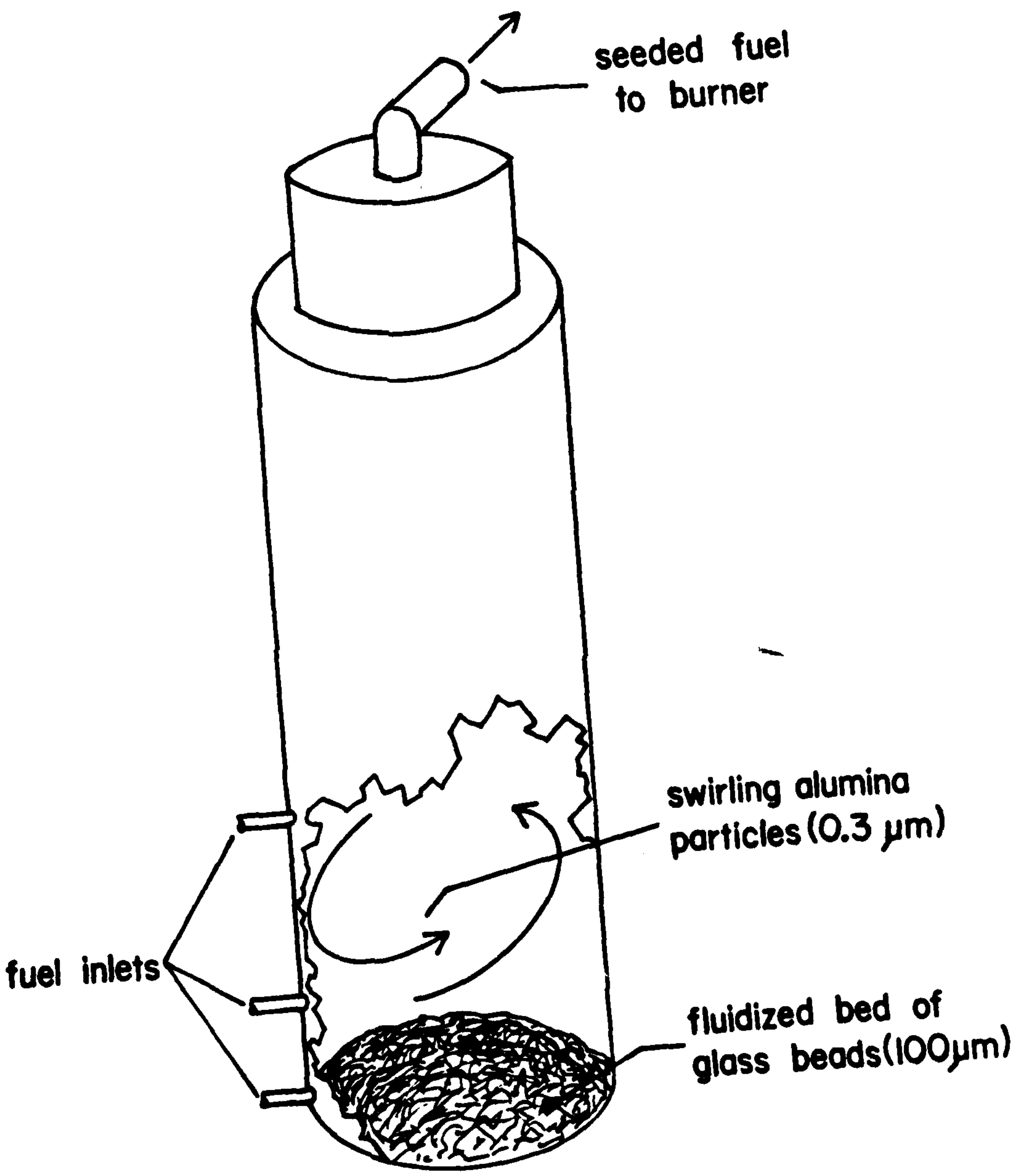


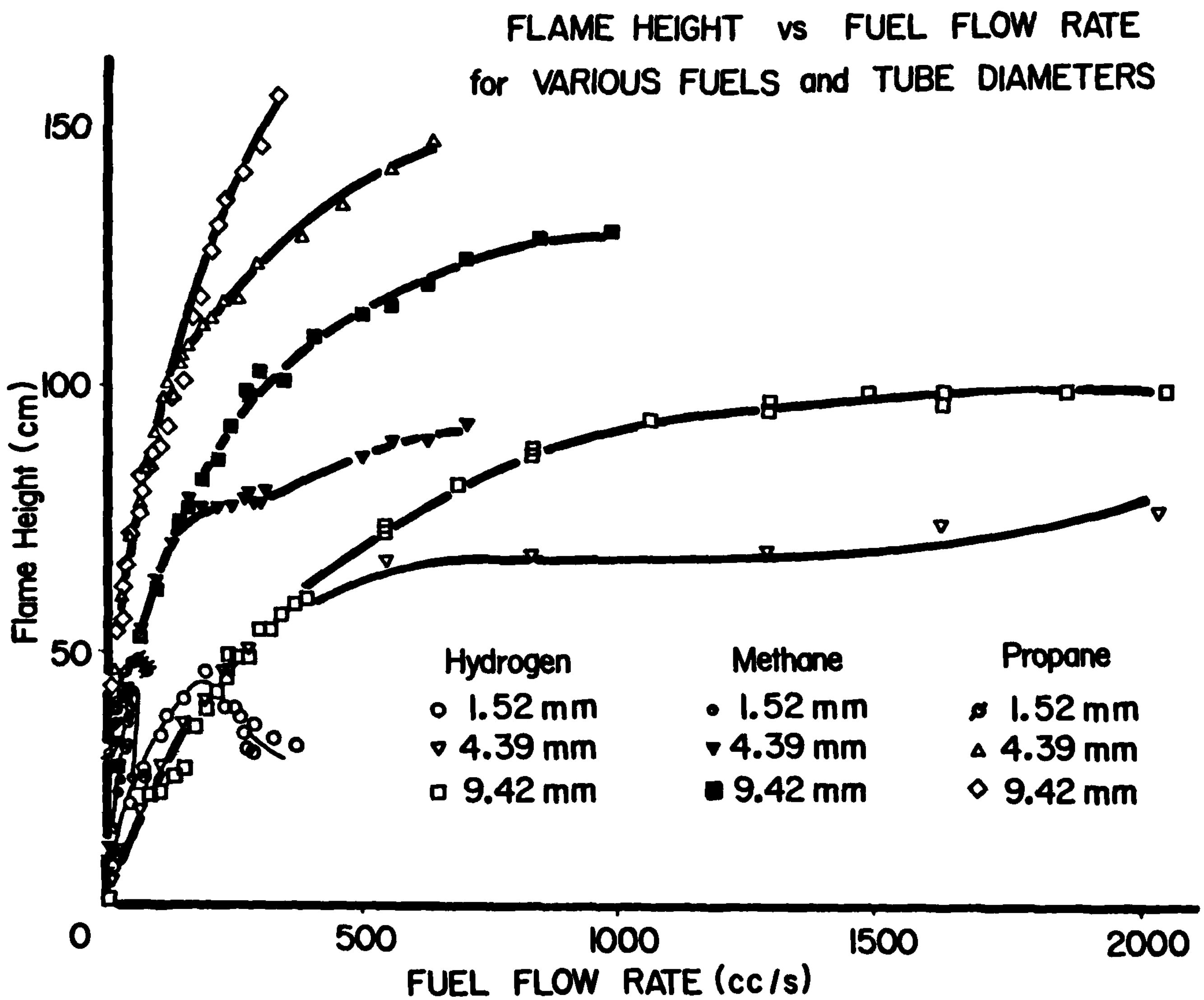
BURNER ASSEMBLY

Figure 1



CYCLONIC FUEL SEEDER

Figure 2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for VARIOUS FUELS and TUBE DIAMETERS
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100
50
0
500
1000
1500
2000
FUEL FLOW RATE (cc/s)
Hydrogen
1.52 mm
4.39 mm
9.42 mm
Methane
1.52 mm
4.39 mm
9.42 mm
Propane
1.52 mm
4.39 mm
9.42 mm

Figure 3

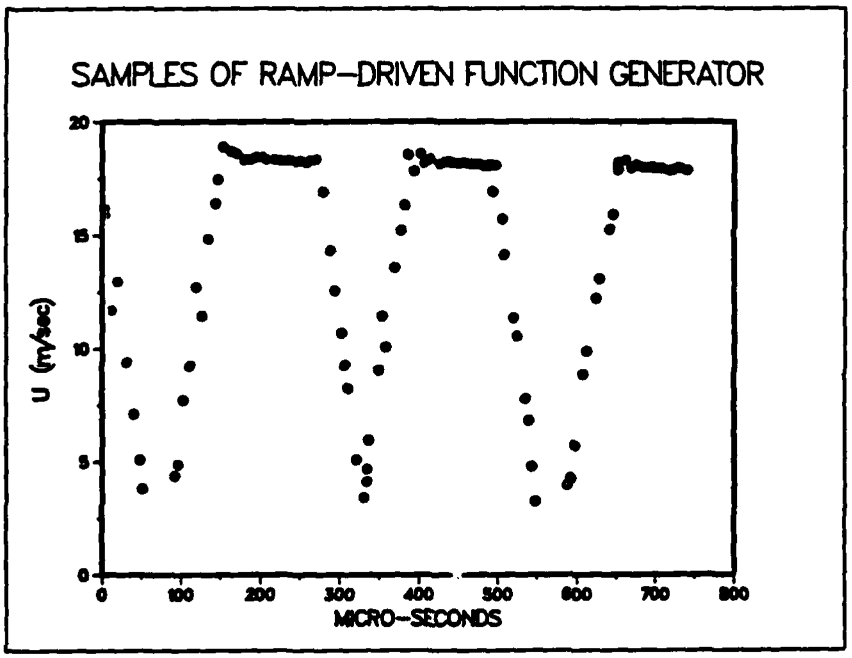
SAMPLES OF RAMP-DRIVEN FUNCTION GENERATOR
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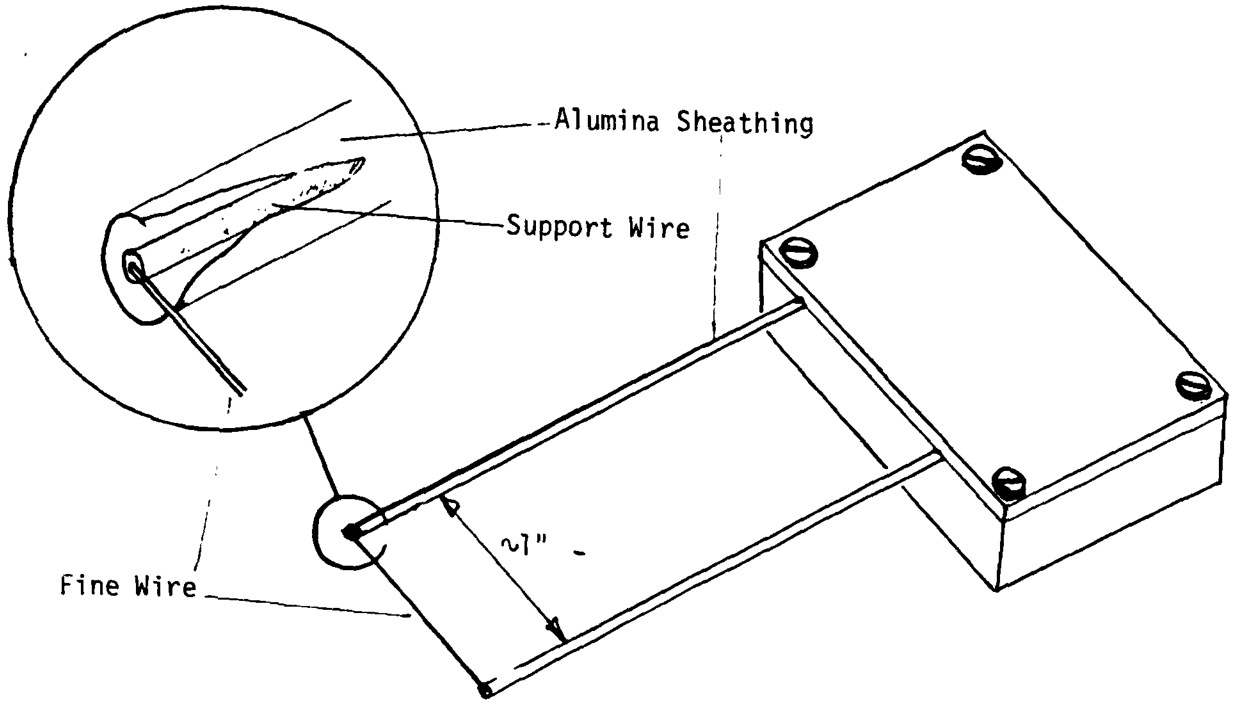
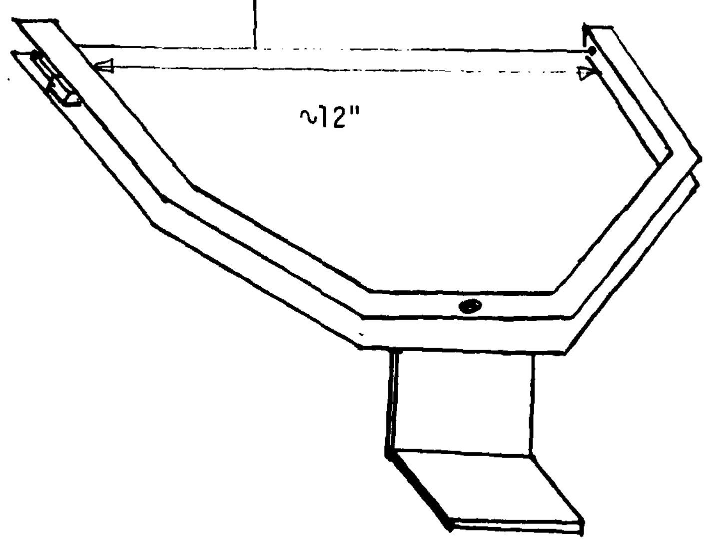
Figure 4



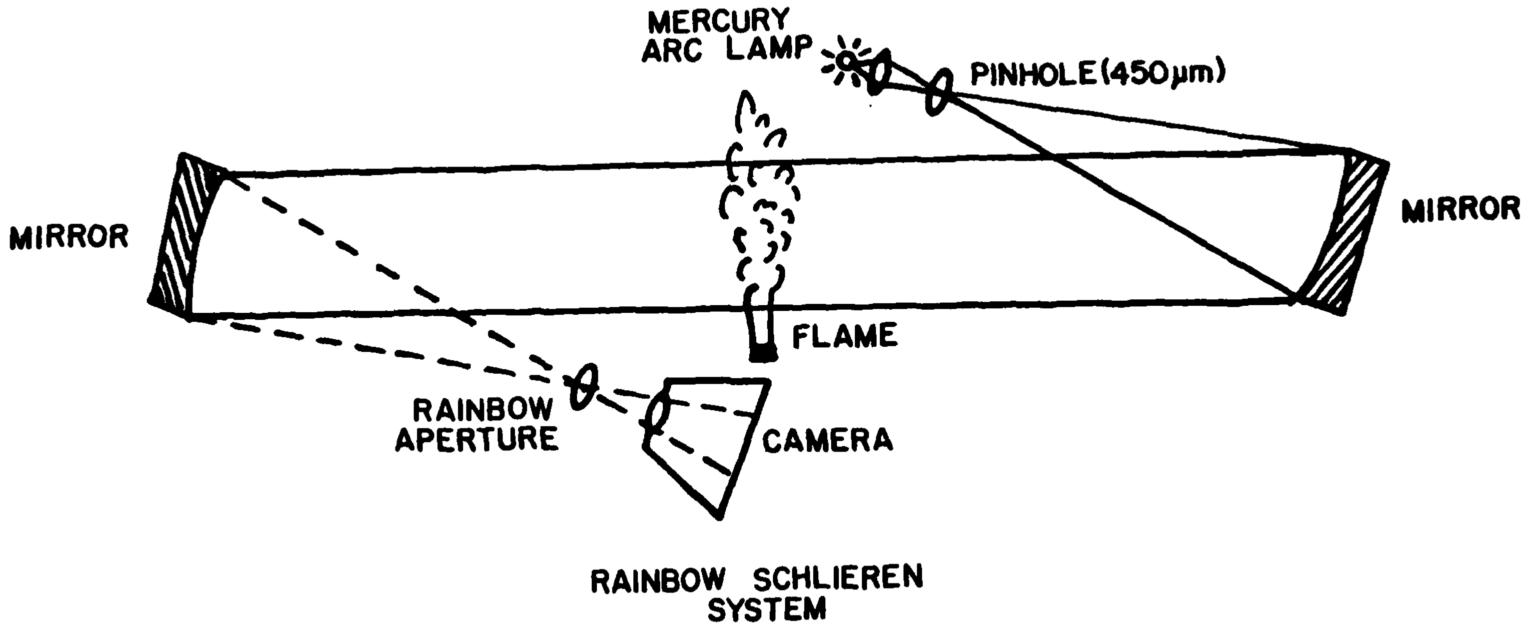
Short Span Thermocouple

Figure 5



Long Span Thermocouple

Figure 6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ARC LAMP
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Figure 7

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